SEARCHES FOR THE HIGGS BOSON AND SUPERSYMMETRY AT THE TEVATRON

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Abstract

The D0 and CDF experiments at the proton-antiproton collider Tevatron have extensively searched for the Higgs boson and signals of supersymmetry using a wide range of signatures. The status of these searches is reviewed with a focus on recent measurements.

1 Introduction

At the Tevatron collider, one of the main challenges is the search for the Higgs boson and for supersymmetric particles. The high integrated luminosities being collected by both the CDF and D0 experiments enable searches with unprecedented sensitivity. At the beginning of 2007, both experiments have recorded data sets of more than $2\,\mathrm{fb}^{-1}$. Recent results obtained with up to $1.1\,\mathrm{fb}^{-1}$ are presented in this note. All limits quoted are at 95% confidence level.

2 Searches for the standard model Higgs boson

In the standard model (SM) the Higgs mechanism is responsible for the electroweak symmetry breaking, thereby generating the masses of the Z and W bosons. As a consequence of this mechanism a single neutral scalar particle, namely the Higgs boson, remains after the symmetry breaking. Assuming the validity of the standard model, global fits to the electroweak data prefer a relatively low mass for the Higgs boson, $m_H = 85^{+39}_{-28}\,\mathrm{GeV}$ [1], while direct searches at the LEP collider set a lower bound on the mass of $114.4\,\mathrm{GeV}$ [2].

At low masses, $m_H \lesssim 135\,\mathrm{GeV}$, the SM Higgs boson dominantly decays via $H \to b\bar{b}$. For the main production channel, which is the gluon-gluon fusion process $gg \to H$ this leads to signatures which are irreducible from QCD production of $b\bar{b}$ pairs. Therefore, at the Tevatron the highest sensitivity for low mass Higgs bosons is obtained from the associated production of the Higgs boson with the weak bosons, i.e. WH and ZH. At high masses the SM Higgs boson predominantly decays into WW boson pairs, which has a manageable background for the $gg \to H$ production mode.

2.1 Low-mass Higgs boson, $m_H \lesssim 135\,\mathrm{GeV}$

Both the CDF and D0 collaborations searched for low mass Higgs bosons using the $WH \to \ell\nu b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$, and $ZH \to \ell\ell b\bar{b}$ production and decay modes. Dominating backgrounds in these searches are the associated production of the weak bosons with $b\bar{b}$ pairs, $Wb\bar{b}$ and $Zb\bar{b}$, as well as the associated production Wjj and Zjj with jets originating from light-flavor quarks, which are falsely identified as b-jets.

The CDF collaboration recently presented a search for the Higgs boson in $WH \to \ell\nu b\bar{b}$ production based on an integrated luminosity of $1\,\mathrm{fb}^{-1}$ [3]. The event selection required a reconstructed electron or muon with a transverse momentum $p_T > 20\,\mathrm{GeV}$, two jets with transverse energy $E_T > 15\,\mathrm{GeV}$ and large missing transverse momentum $\not{E}_T > 20\,\mathrm{GeV}$. The jets were identified to originate from b quarks using secondary vertex (SV) and neural network (NN) tagging algorithms. A resonant peak in the dijet mass distribution, M_{jj},
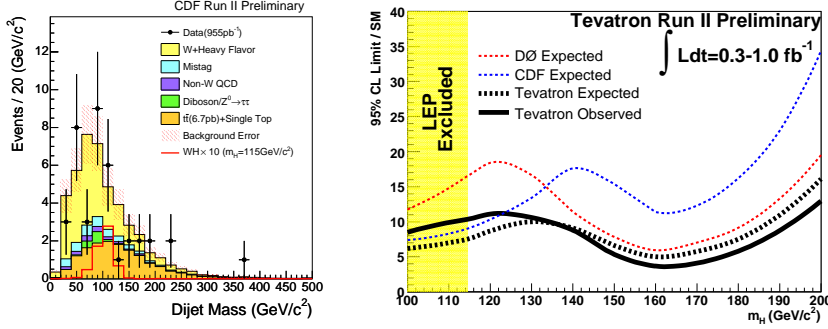
Figure 1: *Left: dijet mass distribution in $W+ \geq 2$ jets events with two secondary vertex tags. Right: combined CDF and D0 limits on SM Higgs production, normalized to the predicted SM cross section.*

indicative of $H \to b\bar{b}$ was searched for. The M_{jj} distribution for events with two heavy-flavor jets identified using the SV tagger is shown in Fig. 1 together with the background prediction and the expected Higgs signal. Upper limits on the production cross sections, σ_{95}, were derived as function of Higgs boson mass m_H. For $m_H \sim 115$ GeV the cross section limit from this measurement alone compared to the SM prediction, σ_{SM}, corresponds to a sensitivity of $\sigma_{95}/\sigma_{SM} \sim 20$.

The search for $ZH \to \nu\bar{\nu}b\bar{b}$ production has also a notable sensitivity to $WH \to \ell\nu b\bar{b}$ as the lepton might be undetected. Based on a data sample of $1\,\text{fb}^{-1}$, the CDF collaboration searched for the Higgs boson in events with large $\not{E}_T$ and two jets, of which one was required to be tagged [4]. In addition to Zjj, a large background contribution was found to be due to QCD multijet production. For $m_H \sim 115$ GeV a sensitivity of $\sigma_{95}/\sigma_{SM} \sim 30$ was separately obtained for ZH and WH production. Combining both production modes the sensitivity was $\sigma_{95}/\sigma_{SM} \sim 16$.

The $ZH \to \ell\ell b\bar{b}$ channel is disfavored due to the low $Z \to \ell\ell$ branching fraction. Nevertheless, the clear event topology provides good background separation. The D0 collaboration recently presented a search in this channel based on an integrated luminosity of $0.9\,\text{fb}^{-1}$ [5]. The analysis required a reconstructed ee or $\mu\mu$ pair with a dilepton mass consistent with the Z boson mass and at least two jets which were required to be identified as b jets using the NN tagger. For central pseudorapidities, $|\eta| < 1.5$, a b-tagging efficiency of 72% at a light-jet fake rate of 4% was obtained. This search and a similar CDF measurement [6] were found to have sensitivities $\sigma_{95}/\sigma_{SM} \sim 25 - 30$ at

$m_H \sim 115\,\text{GeV}$.

2.2 High-mass Higgs boson, $m_H \gtrsim 135\,\text{GeV}$

The dominant decay mode for $m_H \gtrsim 135\,\text{GeV}$ is $H \to WW^{(*)}$. The W decays into an electron or muon are used to suppress the QCD multijet background. As the Higgs boson has spin-0, the final-state leptons are predominately produced with small azimuthal separation due to spin-correlations between them. Therefore, the Higgs signal can be discriminated from the electroweak production of WW boson pairs.

The D0 collaboration performed a preliminary search based on $0.95\,\text{fb}^{-1}$ using the ee, $e\mu$, and $\mu\mu$ final states [7]. At $m_H \sim 160\,\text{GeV}$, where this channel has optimal sensitivity, a cross-section ratio $\sigma_{95}/\sigma_{SM} \sim 4$ was obtained, which excludes models with four fermion families [8] for $m_H \sim 150 - 185\,\text{GeV}$.

2.3 Combined limits on Higgs boson production

The CDF and D0 limits on SM Higgs production were combined for the first time in summer 2006 [9]. Fig. 1 shows the cross-section ratio σ_{95}/σ_{SM} as function of assumed Higgs boson mass m_H. The combination does not yet include all searches presented above. After the conference a new combination with significantly improved cross-section limits was obtained, which also includes additional results obtained since then.

3 Searches for neutral supersymmetric Higgs bosons

Models with two Higgs-doublets, such as the minimal supersymmetric extension of the standard model (MSSM), predict five physical Higgs bosons, of which three (h, H, A) have neutral electric charge. The phenomenology at large $\tan\beta$ (the ratio of the Higgs vacuum expectation values) is remarkable: The cross section for the gluon-gluon fusion process $gg \to H$ and the associated production $b\bar{b}H$ is largely enhanced and the CP-odd A boson is nearly mass-degenerate with either the light or heavy CP even state, h or H, respectively. The leading decay modes of the two mass-degenerate states, both denoted as ϕ, are $\phi \to b\bar{b}$ ($\sim 90\%$) and $\phi \to \tau\tau$ ($\sim 10\%$). Despite the smaller branching fraction, Higgs searches in the di-τ channel have the advantage of a much smaller background level from multi-jet production.

3.1 Supersymmetric Higgs in multi-jet events: $b\bar{b}\phi \to b\bar{b}b\bar{b}$

The D0 collaboration searched for the supersymmetric Higgs boson in the channel $b\bar{b}\phi \to b\bar{b}b\bar{b}$ using the dijet mass distribution in events with three identified
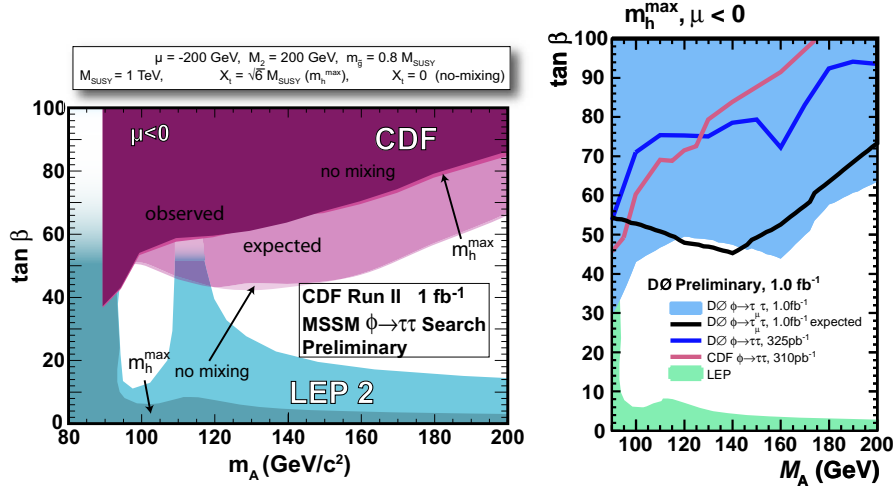
Figure 2: *Excluded regions in the $tan\beta - m_A$ plane obtained by the CDF and D0 collaborations.*

heavy-flavor jets. The published analysis [10] based on an integrated luminosity of $260\,\mathrm{pb}^{-1}$ excludes a region at high $\tan\beta$, e.g. for $m_A \sim 120\,\mathrm{GeV}$ the constraint on $\tan\beta$ is $\tan\beta \lesssim 50 - 60$ (depending on the assumed mixing in the scalar top quark sector). The preliminary update based on $0.9\,\mathrm{fb}^{-1}$ found exclusion limits improved by about a third [11].

3.2 Supersymmetric Higgs decaying to tau pairs: $\phi \to \tau\tau$

Both, the CDF and D0 collaborations searched for the MSSM Higgs boson decaying via $\phi \to \tau\tau$ using data samples of $1\,\mathrm{fb}^{-1}$ each. Whereas the CDF collaboration analyzed τ-decays leading to $e\mu$, $e\tau_h$, and $\mu\tau_h$ final states [12] (with τ_h denoting hadronically decaying τ's), the D0 selection [13] required one τ decaying into a muon. The CDF collaboration observed a small excess of events ($< 2\sigma$, only $e\tau_h$ and $\mu\tau_h$ channels) in the visible mass distribution, which approximates the mass of the hypothetical di-τ resonance. This non-significant excess was not confirmed by the D0 search. The exclusion regions in the plane given by m_A and $\tan\beta$ are shown in Fig. 2. The exclusion regions depend only very mildly on assumptions on the sign of the Higgs mass term μ and the mixing in the scalar top quark sector.

4 Searches for supersymmetry

Supersymmetry (SUSY) is one of the most appealing extensions of the SM, as it solves the hierarchy problem and could provide a candidate for cold dark matter. Supersymmetric models predict the existence of scalar leptons and quarks and spin-1/2 gauginos as super-partners of the standard model leptons, quarks and gauge bosons. R-parity is introduced as a new multiplicative quantum number to differentiate between standard model ($R = 1$) and supersymmetric ($R = -1$) particles. As a consequence of the assumption of R-parity conservation, supersymmetric particles are produced in pairs and the lightest supersymmetric particle (LSP) needs to be stable. In supersymmetric models inspired by supergravity, the lightest neutralino $\tilde{\chi}_1^0$, which is a mixture of the super-partners of the neutral electroweak gauge and Higgs bosons, is usually assumed to be the LSP and is a candidate for cold dark matter. In the following only searches for supersymmetry inspired by minimal supergravity (mSUGRA) and with the assumption of R-parity conservation are presented. Both, the CDF and D0 collaborations performed many searches within other supersymmetric models.

4.1 Gaugino pair production

The associated production of a chargino-neutralino pair, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, can lead to event topologies with three leptons, which has a low SM background. The third lepton might be relatively soft, depending on the mSUGRA parameter space.

Both, the CDF and D0 experiments have searched for the tri-lepton signature taking into account all three lepton flavors and using integrated luminosities up to $1.1\,\mathrm{fb}^{-1}$ [14, 15]. The sensitivity could be increased by not requiring explicit lepton identification for the third lepton and by including final states consisting of a same-sign di-lepton pair. Both experiments derived limits on the cross-section times branching fraction, shown in Fig. 3, which are compared to different mSUGRA inspired scenarios to obtain lower bounds on the chargino mass.

4.2 Scalar quark and gluino production

If sufficiently light, squarks and gluinos could be produced in pairs at the Tevatron. If $M(\tilde{q}) < M(\tilde{g})$, mostly pairs of squarks would be produced, which decay via $\tilde{q} \rightarrow q\tilde{\chi}_1^0$, resulting in an event signature of two acoplanar jets and $\not{E}_\mathrm{T}$. If $M(\tilde{g}) > M(\tilde{q})$, gluinos would decay according to $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ and their pair-production would give topologies with many jets and $\not{E}_\mathrm{T}$. In the case of $M(\tilde{g}) \approx M(\tilde{q})$ and $\tilde{q}\tilde{g}$-production the final state is expected to often consist of three jets and $\not{E}_\mathrm{T}$.
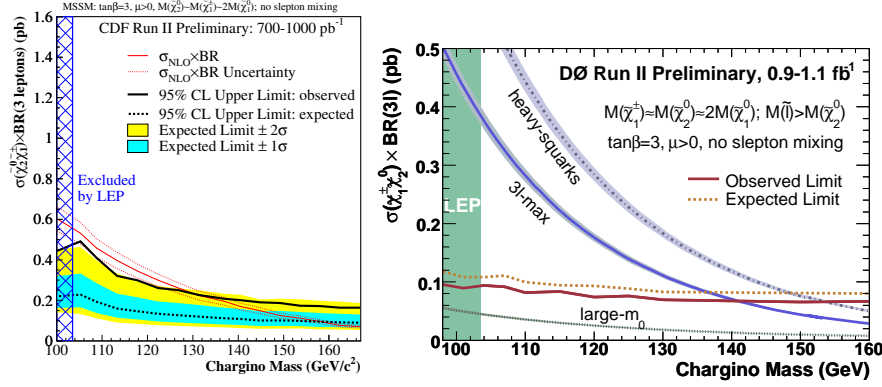
Figure 3: *Limit on associated $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production in comparison with the expectation of several SUSY scenarios obtained by the CDF and D0 collaborations.*

The D0 collaboration searched for the production of squarks and gluinos using three different event selections which were targeted at the scenarios described above [16]. The exclusion region in the plane given by the squark and gluino masses is shown in Fig. 4. For the most conservative assumptions (and for $\tan\beta = 3$, $A_0 = 0$, $\mu < 0$) squark and gluino mass limits of $m_{\tilde{q}} > 375\,\mathrm{GeV}$ and $m_{\tilde{g}} > 289\,\mathrm{GeV}$, respectively, were derived. When interpreting the cross-section limits within mSUGRA the constraints on the common scalar and gaugino masses at the unification scale, m_0 and $m_{1/2}$, could be improved with respect to limits from LEP.

4.3 Scalar top and bottom quark production

Due to a possible large mixing between the super-partners of the left and right handed top (bottom) quarks, the lighter eigenstate of the scalar top (bottom) quark might be significantly lighter than the super-partners of the other quarks. Both experiments searched for the pair production of scalar bottom and scalar top quarks [17, 18, 19]. The scalar bottom quarks were assumed to decay via $\tilde{b} \to b\tilde{\chi}_1^0$ and the scalar top quarks via the loop induced decay $\tilde{t} \to c\tilde{\chi}_1^0$. Exclusion regions in the plane given by the sbottom (stop) and neutralino masses were derived reaching $m_{\tilde{b}} \approx 220\,\mathrm{GeV}$ and $m_{\tilde{t}} \approx 130\,\mathrm{GeV}$, respectively.
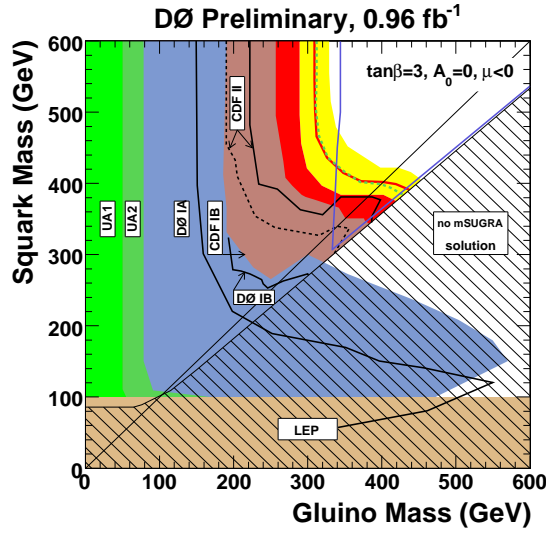
Figure 4: *Exclusion region in the squark and gluino mass plane.*

5   Conclusions and Perspectives

The CDF and D0 experiments at the Tevatron collider have performed a multitude of searches for the standard model and supersymmetric Higgs boson as well as for signals of supersymmetry. At the time of the conference, the searches for the SM Higgs boson which include luminosities up to $1\,\mathrm{fb}^{-1}$ reached a sensitivity of a factor 10 (3) times the SM expectation at $m_H \approx 115\,\mathrm{GeV}$ ($m_H \approx 160\,\mathrm{GeV}$). Imminent improvements of the limits are expected from the increased luminosity and refinements in the b-tagging and the event selection. The "hint" of an MSSM Higgs boson at $m_A \approx 160\,\mathrm{GeV}$ obtained by CDF was not confirmed by D0. No signal for supersymmetry has yet been found at the Tevatron and stringent limits, which are significantly improved compared to Run I, were set. At the beginning of 2007 both experiments have recorded integrated luminosities exceeding $2\,\mathrm{fb}^{-1}$ and are expected to collect much larger data sets during the full period of Run II. Thus, the sensitivity to the production of the Higgs boson and supersymmetric particles will substantially improve in the following years.

References

1. LEP Collaborations ALEPH, DELPHI, L3, OPAL, J. Alcaraz *et al.*, hep-ex/0612034.

2. LEP Working Group for Higgs boson searches, R. Barate *et al.*, Phys. Lett. **B565**, 61 (2003).

3. CDF Collaboration, CDF note 8390.

4. CDF Collaboration, CDF note 8442.

5. D0 Collaboration, D0 note 5275-CONF.

6. CDF Collaboration, CDF note 8422.

7. D0 Collaboration, D0 notes 5063-CONF and 5194-CONF.

8. E. Arik *et al.*, Eur. Phys. J. C **26**, 9 (2002).

9. CDF and D0 Collaborations, CDF note 8384 and D0 note 5227-CONF.

10. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **95**, 151801 (2005).

11. D0 Collaboration, D0 note 5503-CONF.

12. CDF Collaboration, CDF note 8676.

13. D0 Collaboration, D0 note 5331-CONF.

14. CDF Collaboration, CDF note 8653.

15. D0 Collaboration, D0 note 5348-CONF.

16. D0 Collaboration, D0 note 5312-CONF.

17. CDF Collaboration, CDF note 8411.

18. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **97**, 171806 (2006).

19. V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **645**, 119 (2007).